Ultra high energy cosmic rays and neutrinos after Auger

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Abstract

We discuss the main results that were recently published by the Auger Collaboration and their impact on our knowledge of the ultra high energy cosmic rays and neutrinos.

1 Introduction

We have discussed the problems related to the ultra high energy cosmic rays (UHECR) quite many times in recent years after the results of the high resolution Fly's Eye (HiRes) started trickling out several years ago. The cosmic ray energy spectrum extracted from the the HiRes observations indicated that the spectrum suffers a strong decrease at energies above 5×10^{19} eV [1], consistent with the GZK cutoff [2] that is due to UHECR interactions with the microwave background. There was thus a strong disagreement with the energy spectrum derived from the previous largest exposure cosmic ray air shower array, Agasa [3] that seemed to continue with the same slope above 10^{20} eV.

HiRes and Agasa measure the cosmic ray events in different ways. HiRes is a fluorescent detector that follows the shower longitudinal development by detecting the fluorescent light emitted by the Nitrogen atoms in the air ionized by the shower charged particles. The primary cosmic ray energy is obtained from integration of the shower longitudinal profile normalized by the average electron energy loss and the fluorescent efficiency of the air.

Agasa, on the other hand, is a classical air shower array that records the particle density at the observation level and uses Monte Carlo calculations to relate it to the primary cosmic ray energy. The dependence of this method on the hadronic interaction model used in the simulations is considered stronger in this approach.

In 2007 the first results of the Pierre Auger Observatory (PAO) in Argentina were published. This experiment became the hope for better understanding of UHECR several years ago when its construction started. It is a hybrid air shower experiment that applies both detection methods. PAO consists of an air shower array of area 3,000 km^2 where the individual detectors are 10 m^2 water tanks placed at distances of 1.5 km in a hexagonal pattern (SD). The shower array is surrounded by 24 fluorescent telescopes (FD) located in four groups of six. The idea is that during cloudless moonless nights when the fluorescent detectors can work the UHECR showers will be observed simultaneously by both types of detectors and this *hybrid* observation will unveil better the shower properties. Here is a brief summary of the Pierre Auger Observatory results.

The energy spectrum derived from PAO data [4] shows a feature consistent with the GZK cutoff similar, but not identical to that of HiRes - see Fig. 2. The spectrum is based on the much higher surface detector statistics normalized to the energy estimates of the fluorescent detector in hybrid events. The problem is that if the energy was estimated only from the SD data (particle density at 1,000 meters from the shower core - S_{1000}) the energy scale would be 25% higer [5]. Formally this is not a big problem because the uncertainty of the energy estimate is 22%.

Another problem appears when PAO attempts to estimate the type of the primary cosmic ray nuclei. When it is estimated from the depth of the shower maximum measured by the fluorescent detector X_{max} the average primary mass appears to be close to He [6] . If the surface detector density S_{1000} is used to estimate the number of shower muons [5] the average primary nuclei appear to be much heavier. The preliminary conclusion from these two disagreements is that showers are absorbed in the atmosphere slower than models predict.

The Auger Collaboration succeeded, however, to eliminate a class of UHECR models that predicted that the primary particles are gamma rays. From studies of X_{max} and other shower properties the fraction of gamma rays in the cosmic rays above 10^{19} eV is limited to not more than 2% [7]. The much smaller statistics at higher energy does not allow for such strong limits, but at least the bulk of UHECR, which we consider extra galactic, consists of nuclei.

The Auger result that impressed the most not only the astrophysical community, but also the general public, was the published correlation of their highest energy events with active galactic nuclei [8, 9]. Twenty of the 27 events of energy above 5.7×10^{19} eV (57 EeV) come within 3.1^o of the position of AGN at redshift smaller than $\leq$0.017 (distance of 71 Mpc) while one expects only 7 in case of isotropic source distribution. The 3.1^o circle around the event direction (that was obtained from a scan in energy, angle and distance) is understood as scattering in the galactic magnetic field plus about 1^o Auger angular resolution. Accounting for the number of scans the chance probability is well below 1%. If the events that come from galactic latitude less than 10^o (where catalogs are not full and cosmic ray may scatter more) are excluded then 19 out of 21 events are closer than 3.1^o from nearby AGN.

Since the Auger collaboration published the arrival directions and energies of these 27 events in Ref. [9] this announcement was quickly followed by a number of other analyses and questions, like:

• why only 71 Mpc when >60 EeV cosmic rays should come from distances up to 200 Mpc ?

• why there are no events from the direction of the Virgo cluster, that contains powerful AGN ?

• what does the concentration of events from directions close to Cen A means ?

Many of these questions were also asked by the Auger Collaboration [9].

2 UHECR energy spectrum

2.1 Formation of the cosmic ray spectrum in propagation

The energy spectrum at energies above 10^{18} eV depends mostly on two parameters: the acceleration spectrum at the sources and the source distance distribution, as the spectrum detected at Earth evolves in propagation in the universal photon fields. Most of the propagation calculations used for the determination of the acceleration spectrum have been done in two simplifying assumptions:

• All sources have identical acceleration spectra, and

• Sources are isotropically distributed in the Universe.

Since the energy of the background photons is much lower than 1 eV the center of mass energy for $p\gamma$ interactions is low, at the threshold for photoproduction interactions. The cross section of the $p\gamma$ photoproduction interactions is very well known from accelerator measurements - see Fig. 3 in

Ref. [10] as well as the fractional proton energy loss per interaction. Another energy loss process for protons is the e^+e^- Bethe-Heitler pair production [11, 12] where the proton energy loss peaks at about 10^{19} eV and the adiabatic energy loss due to the expansion of the Universe. The energy loss length for protons is shown in Fig. 1.

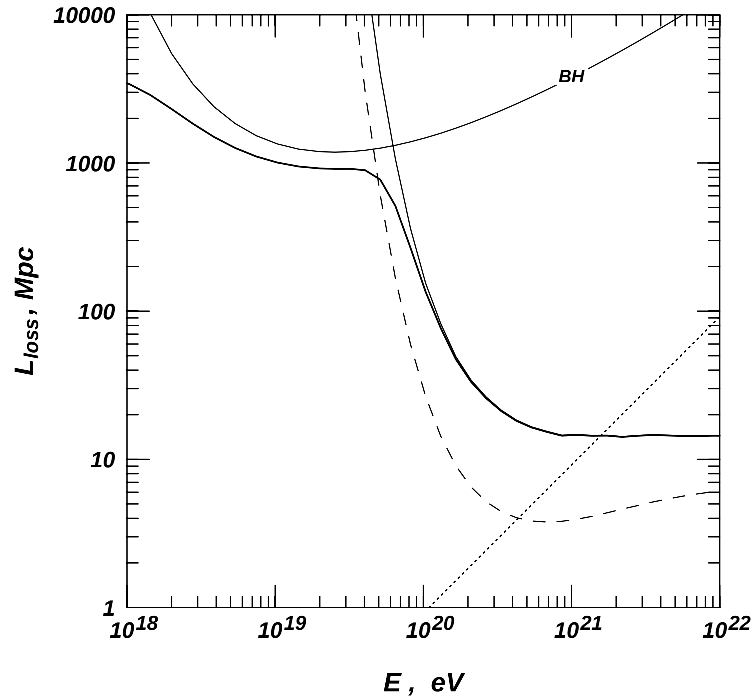

Figure 1: The dashed line shows the photoproduction interaction length and thick solid one - the total energy loss length including the pair production process, labeled as BH. The neutron decay length is plotted with a dotted line.

Nuclei heavier than H in addition to photoproduction and pair production (scaled by Z^2 and shifted up in total energy by A) suffer from a different energy loss - photo disintegration [13]. There are two main processes - one nucleon loss at the giant nuclear resonance and two nucleon loss at higher photon energy in the nucleus frame. One has also to account for the decay of unstable nuclei generated this way.

If UHECR are protons there are two general solutions for the cosmic ray acceleration spectrum - relatively steep acceleration spectrum $E^{-(\gamma+1)}$ with no cosmological evolution of the sources (a lá Berezinsky [14]) and a much flatter (γ = 1.2-1.3) with a strong cosmological evolution such as that of the

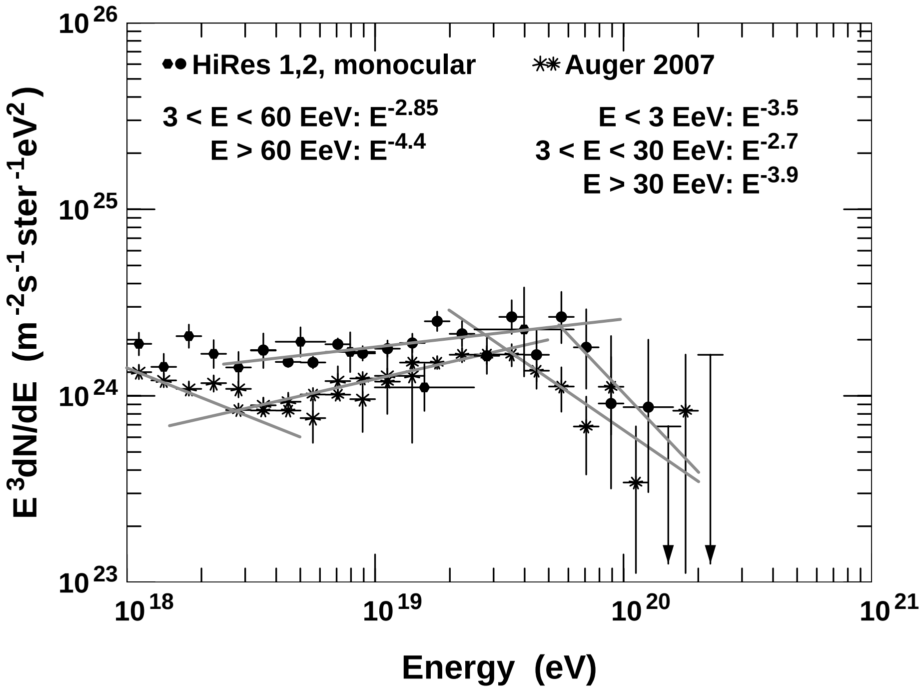

Figure 2: Cosmic ray energy spectra derived from data by the Auger and HiRes Collaborations. The two types of data points for Auger give the SD and hybrid data sets. The monocular spectra of HiRes 1 and 2 are shown for HiRes.

star forming regions (SFR). The cosmological evolution is not important for the highest energy cosmic rays that can not come to us from redshifts higher than 0.05 but does affect lower energy ones. Note that the first ('dip') model does not need any galactic cosmic rays above about 10^{18} eV. Mixed composition models [15] generally do not require any cosmological evolution of the UHECR sources and are consistent with acceleration spectra with γ = 1.2-1.3.

2.2 Experimental data

Figure 2 compares the cosmic ray energy spectra derived by the Auger and the HiRes Collaborations. The lines drawn through the data points are rough fits of the spectra in limited energy ranges. Note these are not identical to the fits made by the Auger collaboration [16]. Apart from the overall normalization of the two spectra they show a small difference in shape that is still statistically not very significant but currently favor different astro-

physical models. The HiRes spectrum [17] is fully consistent with the model of Berezinsky et al that involves a steep acceleration spectrum ($\gamma = 1.7$). The 'dip' at about $3{\times}10^{18}$ eV is formed at the edge of pair production and adiabatic energy loss. There are several good fits to the Auger energy spectrum performed by the collaboration itself [16]: a steep proton acceleration spectrum with $\gamma = 1.55$ without cosmological evolution, a flatter one with $\gamma = 1.3$ and strong $(1+z)^5$ cosmological evolution, and a mixed composition spectrum with $\gamma = 1.2$ Some of these fits require the galactic cosmic ray spectrum to extend above $10^{18.5}$ eV. It is worth noting that if the Auger energy scale were 25% higher, the spectrum would be much closer to the HiRes one in both overall normalization and in the position of the GZK feature and that they predict different chemical compositions of UHECR.

3 Secondary particle fluxes from cosmic ray propagation

The energy that UHECR lose in propagation end up in fluxes of gamma rays and neutrinos from π^0 and $\pi^\pm$ decays. Gamma rays have even shorter energy loss length than nuclei and develop pair production/inverse Compton cascades where synchrotron radiation may play important role. In the presence of noticeable (1 nG) extragalactic field 10^{18} eV electrons quickly lose energy to GeV synchrotron photons.

Neutrinos, however, have very low interaction cross section and arrive at Earth with just redshift energy loss from almost any distance. For this reason the cosmological evolution of the cosmic ray sources are very important input in the calculation of these *cosmogenic* [18, 19] neutrinos.

Two among the Auger results presented above may have an important connection to the flux of cosmogenic neutrinos - the correlation of the highest Auger events with nearby AGN and the $(1+z)^3$ cosmological evolution evolution required by one of the spectrum fits with relatively flat ($\gamma = 1.3$) proton models.

3.1 Cosmological evolution of AGN

The cosmological evolution of AGN has been studied by their X-ray emission as a function of the redshift. Most of the X-ray satellite measurements were sensitive to relatively low energies and the worlds richest data set is in the 0.5 to 2 KeV range. Anyway it is very difficult to know what the best proxy is for the evolution of the cosmic ray luminosity, but the available astronomical

data are either in infrared (for the SFR) or in low energy X-rays.

The AGN observations of the Rosat satellite were analyzed in Ref. [20] and the derived cosmological evolution is $(1+z)^5$. A later analysis [21] used much larger statistics and was able to divide the observed AGN in four luminosity groups, each encompassing one order of magnitude above 10^{42} erg/Mpc^3. It turns out, according to this analysis, that the highest X-ray luminosity AGN also have the highest luminosity evolution: $(1+z)^7.1$ up to $z_{max} = 1.7$. Such cosmological evolution would indeed generated very high fluxes of cosmogenic neutrinos.

There are not, however, many such AGN and it is not very likely that they are the sources of UHECR that have to come (according to the analysis in Ref. [9]) from many nearby sources. It maybe better to use for this purpose the cosmological evolution of the AGN X-ray luminosity that could be obtained by summation from the data published in Ref. [21] and is shown in Fig. 3. Up to redshifts exceeding 1 the total AGN luminosity has $(1+z)^5$ cosmological evolution, significantly stronger than the evolution of star forming regions.

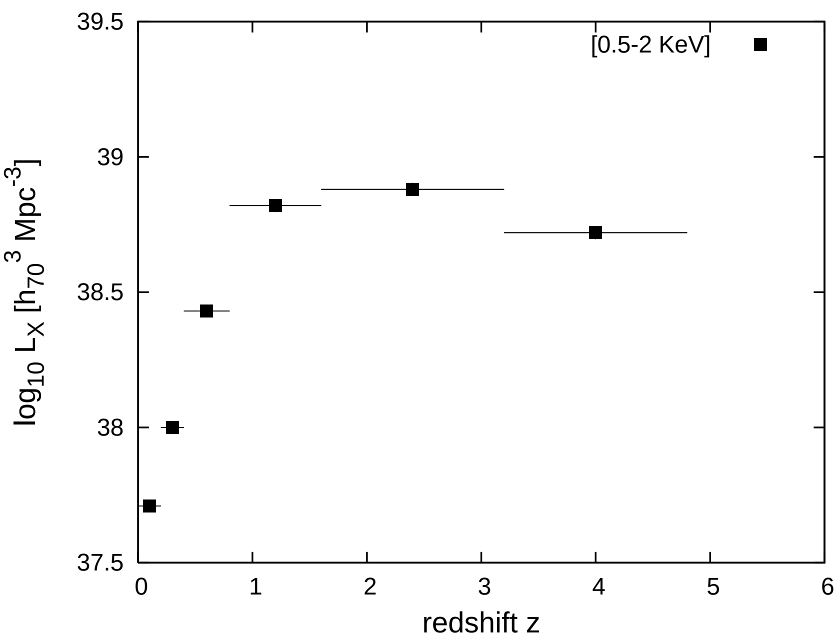

Figure 3: Total X-ray AGN luminosity as a function of redshift. Values are integral from the luminosity table of Ref. [21].

3.2 Fluxes of cosmogenic neutrinos

In addition to the cosmological evolution of the cosmic ray sources the flux of cosmogenic neutrinos depends on a number of parameters:

- The average acceleration slope of the highest energy cosmic rays (UHECR)
- The maximum acceleration energy E_{max}.
- The distribution of the cosmic ray sources in the Universe. This is important to estimate the average UHECR emissivity since we only observe UHECR generated in our cosmological neighborhood, i.e. $z < 0.40$. Auger analysis requires source density higher than 3.5×10^{-5} Mpc^{-3}. (Number sources within 75 Mpc ¿ 61)

We will use the following parameters in calculation of the cosmogenic neutrino flux:
UHECR emissivity of 2.25×10^{44} erg/Mpc^3, i.e. one half of the value derived by Waxman and used in an earlier calculation [22]
acceleration spectrum with $\gamma = 1.3$ with an exponential cutoff at $10^{21.5}$ eV
cosmological evolution $(1+z)^5$ up to $z_{max} = 1.7$, then flat to $z = 2.7$ with exponential decline after that
cosmological model with $\Omega_\Lambda = 0.73$
and new neutrino yields calculated with the same cosmological model for interactions on the microwave background

Figure 4 compares the spectrum of all four neutrino flavors calculated in this way to that of the previous calculation based on Waxman's parameters [23]. Note that the higher energy peak consists mostly of ν_μ, $\bar{\nu}_\mu$ and ν_e while the lower energy one represents $\bar{\nu}_e$ from neutron decay. The contribution of electron anti neutrinos to the higher energy peak comes from neutron interactions and is small as most neutrons decay. Although the fluxes are not very distant from each other there are several significant differences:
• The Auger inspired flux cuts off at lower energy because of its steeper acceleration spectrum in spite of the identical maximum energy. If the maximum energy were lower the total normalization of the flux would be lower and the cutoff would be scaled down.
• The peaks in the neutrino energy distribution are slightly higher but at somewhat lower energy. Both effects can be related to the higher contribution of high redshifts.

It is difficult to estimate correctly the detectable event rates from these two distributions, but the Auger inspired fit is certainly much less efficient in

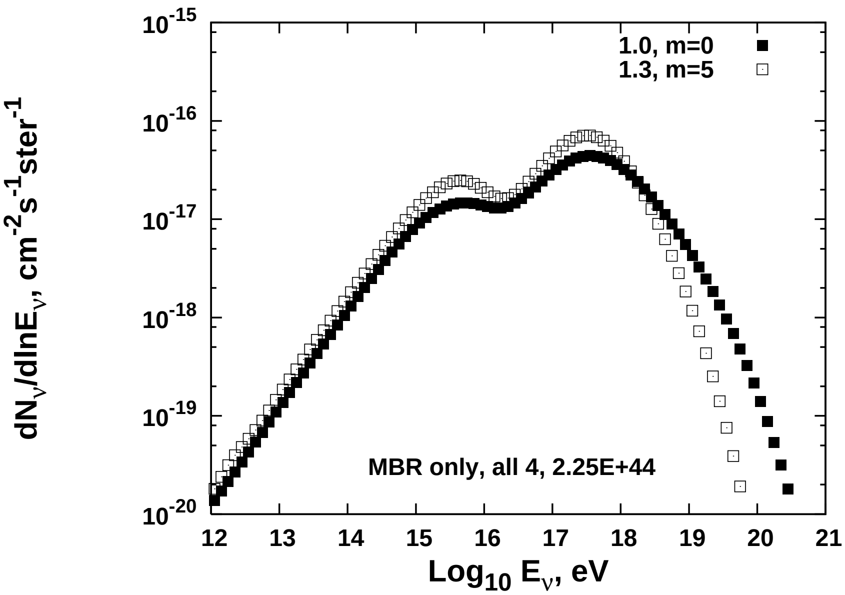

Figure 4: Comparison of the flux of cosmogenic neutrinos to that of Ref. [22]

production of very high energy neutrinos that could be detected by experiments such as ANITA and generally all experiments based on radio detection of neutrino induced showers.

A full calculation of the cosmogenic neutrino fluxes should also include neutrinos from interactions in the infrared/optical background. In such a calculation the relatively flat acceleration spectrum would not make a huge difference although the infrared background contribution would be stronger than the one for $\gamma = 1$ spectrum. The strong cosmological evolution of the sources would also not be very important since the infrared background evolves not as fast as the microwave one.

3.3 Effects of the cosmic ray composition

Models of UHE cosmic rays accelerated in a mixed cosmic ray composition generate cosmogenic neutrino fluxes with a different shape. Since the energy measured by air showers is the total energy per nucleus such models generate smaller high energy peaks and much higher lower energy one from neutron decays after disintegration. The photoproduction threshold is proportional to the nuclear mass, A times higher then 3×10^{19} which is the proton threshold for interactions in MBR. He nuclei would then start

interacting at energy higher than 10^{20} eV and iron nuclei - above 10^{21} eV. Although the maximum energy achieved in acceleration depends on the nuclear charge Z such nuclei may not exist and the mixed composition models tested by Auger only extend to 10^{20} (10^{21}) eV, i.e. the energy per nucleon does not reach the He (Fe) photoproduction threshold.

The first approximation for the flux of cosmogenic neutrinos generated by mixed composition models is that only their proton component undergoes photoproduction interactions. This, however, is not well defined either because the cosmic ray composition continuously changes in propagation - it becomes lighter as nuclei disintegrate. A good estimate can only be obtained by a direct Monte Carlo simulation assuming a particular cosmic ray composition at the sources. Assuming a composition introduces some more free parameters in the calculation. It is important to note that the lower energy $\bar{\nu}_e$ peak is below the Glashow resonance energy and would not give a high neutrino interaction rate.

4 Conclusions

The first results of the Auger Collaboration did improve our knowledge of the ultra high energy cosmic rays. They are fully consistent with a GZK feature in the cosmic ray spectrum as suggested previously by the HiRes Collaboration. Being a hybrid experiment Auger demonstrated that the energy estimate by fluorescent detectors and surface air shower array is different, as previously suggested by the Agasa and HiRes spectra. Now the UHE community is searching for the reasons for this disagreement that may hide in the currently used hadronic interaction models.

Auger started the direct search for the sources of UHECR by studies of the correlation of their highest energy events with active galactic nuclei. The published correlation inspired many other different analyses of correlation with powerful astrophysical objects. This work is in progress now and the UHECR sources will be identified eventually when the Auger statistics grows - it will double at the end of August 2008.

Since the current UHECR energy spectrum can be fit with several different models it is not obvious that we know better the expected flux of cosmogenic neutrinos. This may only happen when an unique fit of the spectrum is achieved.

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DISCUSSION

DANIELE FARGION In your last paper few weeks ago the main conclusive sentence was: Following our 1995 paper one could think the Auger events may reach us from Cen A. I could not find this prediction in that paper.

TODOR STANEV

I should not have used a similar statement in the conclusions since this option was not really discussed in the paper. What I had in mind and tried to lead to is that with reasonable magnetic fields (order of 1 μG) in the Cen A lobe one can imagine UHECR accelerated at that object to bend at significant angles and appear to the observer as coming from nearby sources.

SERGIO COLAFRANCESCO It seems to me that you are assuming a single population of AGN in your calculations and not accounting of their astrophysical differences. What are the implications of such an assumption on your results.

TODOR STANEV You are absolutely correct, Sergio. All current estimates are done in the assumption that all sources have identical parameters. There are only a few attempts to account for differences choosing a certain type of source and a luminosity and maximum energy for each source (see P.L. Biermann and students work). Unfortunately in such analyses one has to rely on simple theoretical calculations of these important parameters. One can easily fit the UHECR spectrum in such models as they introduce more 'free' parameters.